PICTURE OF THE MONTH

A High-Resolution Lightning Map of the State of Colorado

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ABSTRACT

For the state of Colorado, 10 years (2003–12) of 1 April–31 October cloud-to-ground (CG) lightning stroke data are mapped at 500-m spatial resolution over a 10-m spatial resolution U.S. Geological Survey (USGS) digital elevation model (DEM). Spatially, the 12.5 million strokes that are analyzed represent ground contacts, but translate to density values that are about twice the number of ground contacts. Visual interpretation of the mapped data reveals the general lightning climatology of the state, while geospatial analyses that quantify lightning activity by elevation identify certain topographic influences of Colorado’s physical landscape. Elevations lower than 1829 m (6000 ft) and above 3200 m (10 500 ft) show a positive relationship between lightning activity and elevation, while the variegated topography that lies between these two elevations is characterized by a fluctuating relationship. Though many topographic controls are elucidated through the mappings and analyses, the major finding of this paper is the sharp increase in stroke density observed above 3200 m (10 500 ft). Topography’s role in this rapid surge in stroke density, which peaks in the highest mountain summits, is not well known, and until now, was not well documented in the refereed literature at such high resolution from a long-duration dataset.

1. Introduction

In map form, lightning climatologies reveal variations in lightning activity across an area. This cartographic information benefits a wide range of entities including those that maintain networks and infrastructures vulnerable to lightning and those with interests in hydrology and wildland fire management. In Colorado and other mountainous regions with abundant summertime outdoor recreation opportunities, a high-resolution lightning climatology map is particularly relevant from a lightning hazards perspective. In meteorology and regional climatological studies, the ability to document lighting attachment patterns at fine scales across a variegated landscape contributes a deeper understanding of thunderstorm behavior (Cummins 2012; Hodanish and Wolyn 2011; Barker Schaaf et al. 1988) and can support and refine empirically derived conclusions that result from shorter-duration datasets and/or from a more coarse spatial analysis.

A primary motivating factor for this work is that there is no comprehensive cloud-to-ground (CG) lightning climatology for the state of Colorado in the formal literature. The most formal comprehensive work that analyzes CG lightning in Colorado was published by Lopez and Holle (1986). The authors examine a single year (1983) of CG lightning data collected over the state’s northeast region where they found the lightning activity to be mainly a warm season event, with a large majority of the flashes occurring June through September. Other results of the work by Lopez and Holle (1986) show that lightning activity ranges from extremely intense with some days experiencing 5-min flash rates in excess of 100, to thunderstorms producing less than 10 flashes in a 5-min period. Geographically, Lopez and Holle (1986) found that maximum flash concentrations were aligned north–south along the eastern slopes of the Colorado...
Front Range, and then southeast to east along the north facing slopes of the Palmer Divide.

In another investigation, Reap (1986) analyzed two years (1983 and 1984) of June through September lightning data and other remotely sensed meteorological variables over the western United States, including Colorado, using a grid size of $47 \times 47 \text{km}^2$. A high correlation was found between terrain elevation and the hour of maximum frequency of lightning; the higher the elevation, the earlier the onset of lightning activity. The author concluded that a fairly stable seasonal distribution and a generally homogeneous geographical distribution of lightning activity exists over the western United States, generally west of $103^\circ \text{W}$ longitude. The consistent spatial and temporal distribution observed was likely the result of the strong control exerted by the underlying topographical features characteristic to that part of the United States.

Building on the successes of the works of Lopez and Holle (1986), Reap (1986), and others who have examined components of lightning activity in some or all of the Colorado landscape (e.g., Orville and Huffman 2001; Zajac and Rutledge 2001; Boccippio et al. 2001; Barker, Schaat et al. 1988), a lightning climatology paper by Hodanish and Wolyn (2011) comprehensively analyzed lightning patterns over Colorado. This informal paper (e.g., not peer reviewed) analyzed 17 yr of CG flash data on a 1-km spatial resolution map. The authors found that mountainous regions that had access to a continued source of low-level moisture had the largest concentrations of CG lightning. These areas included the mountain–plains interface and the southern exposure of the San Juan Mountains. Mountainous terrain that did not have access to a continued source of available moisture experienced significantly less CG activity. It was also hypothesized that a certain meteorological regime, known as the Denver Cyclone vorticity zone (DCVZ; Szoke et al. 1984), plays a key role in both enhancing and limiting the lightning activity across the greater northeast Colorado region. The authors also noted that large valley regions surrounded by mountains show noticeable minimums in lightning activity.

The purpose of the current paper is to demonstrate that a set of geospatial analytical tools can be used to build upon the Hodanish and Wolyn (2011) findings and ultimately create a high-resolution statewide lightning climatology. Advantages of our approach lie in the opportunity to visually explore vast datasets in map form, a research format that facilitates visual thinking (MacEachren et al. 2004), and in the ability to generate quantitative results over discrete geographical regions. Similar in methodology to the work of Cummins (2012) who incorporated measures of digital elevation model (DEM) terrain surface roughness in a lightning study, our approach is made possible through the use of a suite of geospatial tools that are managed in a geographic information system (GIS). A GIS is a mapping technology that enables users to interact with and analyze maps and other sources of data. In this study, we used GIS and its sophisticated analytical methods to visualize the relationship between lightning activity and elevation and to quantify this relationship in 152 m (500 ft) elevation classes. The paper first discusses the data and the data processing. This is followed by a brief discussion of the lightning climatology of Colorado. Next, the focus shifts to a demonstration of the utility of GIS in quantitative lightning climatology studies through the characterization of lightning activity by elevation.

2. Data

Lightning detection in the state of Colorado has been ongoing since the 1970s. The Bureau of Land Management (BLM) was first to use such a system in order to provide early warning of fire starts and to direct resources to potential fire initiation locations (Krider et al. 1980). Throughout the 1980s, the BLM system was upgraded (Reap 1986), and in 1989 it was combined with other regional lightning detection systems across the United States (Orville et al. 1983; Mach et al. 1986) to form the U.S. National Lightning Detection Network (NLDN; Orville 2008, 1991). The NLDN itself has gone through numerous upgrades and expansions through the 1990s and 2000s (Cummins et al. 1998, 2006), and is now known as the North American Lightning Detection Network, operated by Vaisala (Orville et al. 2002). The NLDN detects CG lightning flashes and strokes over North America with a stroke detection efficiency of 60%–80% (during 2003–12), a flash detection efficiency of 90%–95%, and a spatial accuracy of 250 m (Cummins and Murphy 2009).

Most negative CG flashes consist of multiple strokes, and about half of these flashes have multiple ground contact points (GCP; Stall et al. 2009; Cummins and Murphy 2009). On average, a negative CG flash will have from 1.45 to 1.7 GCP per flash (Valine and Krider 2002). These individual GCPs can be separated over a range of tens to hundreds of meters. In this paper, stroke data are analyzed. Spatially, strokes characterize the GCP distribution, but represent about twice the number of actual GCPs.

Recognizing the significant 2002–03 NLDN improvements in stroke detection efficiency (Cummins and Murphy 2009), the dataset examined in our study excludes the years prior to 2003. The dataset examined in this paper covers the 10-yr period 2003–12. The 2002–03 NLDN upgrades are evident when comparing stroke
density by elevation class between two periods (1996–2002 and 2003–12) over the state of Colorado (Fig. 1). The later years (2003–12) show a marked increase in stroke density in the higher elevations above about 3200 m (10,500 ft). The twenty-three 152-m (500 ft) elevation classes in Fig. 1 serve to outline the relationship between stroke density and elevation, and are examined in greater detail in section 5.

November through March are not included in the dataset because these months capture a negligible portion (less than one-half of 1%) of Colorado’s annual lightning activity (Hodanish and Wolyn 2011). Last, as with other CG lightning research, positive polarity strokes less than 15 kA were excluded from the dataset (Cummins and Murphy 2009; Rudlosky and Fuelberg 2010; Orville et al. 2011). The resulting number of strokes examined over the 10-yr period is 12.5 million.

3. Data processing

A statewide 10-m² spatial resolution U.S. Geological Survey (USGS) DEM serves as a base map for our explorations. A DEM is a gridded array of elevation values that represent a sampled number of ground positions. The statewide DEM is utilized to visualize the topographic features of Colorado, such as mountains, valleys, plateaus, and plains, and serves as a platform from which to quantify lightning activity by elevation in a GIS.

The 2003–12 NLDN dataset and underlying DEM are mapped in ESRI’s ArcMap 10.2 GIS software environment.
A 500-m² vector fishnet consisting of approximately 1.1 million cells was created within the political boundaries that define the state of Colorado. A point-in-polygon count generates a 500-m² raster image with each cell’s value representing the average annual strokes received in each cell multiplied by 4 to represent stroke density at 1 km² across the state of Colorado (Fig. 2). The 152-m (500 ft) elevation ranges serve as templates through which terrain elevation is visualized and from which stroke count statistics are calculated (Fig. 3). Though represented here as two different maps (Figs. 2 and 3), in a GIS environment, the information on both maps can be viewed as one scene and the transparency of both maps can be adjusted to explore spatial relationships.

4. Summary of Colorado’s lightning climatology

At 2070 m (6800 ft), Colorado has the highest mean elevation of any state in the United States. Elevations range from 1010 m (3315 ft) in the northeast section of the state where the Arikaree River flows into Kansas to 4399 m (14433 ft) at the summit of centrally located Mount Elbert (U.S. Geological Survey 2013). Stroke densities in the state range from 30 km² yr⁻¹ to less than 1 km² yr⁻¹. The greatest stroke densities occur in the higher elevations of the mountains, though these maxima vary from mountain range to mountain range. Areas of high stroke densities occur along the gradual slope of the mountain–plains interface, focusing over east–central Colorado (Palmer Divide/Pikes Peak region) and along the Colorado–New Mexico border (Raton Mesa region) (Fig. 2). Minimum stroke densities occur over the San Luis Valley, along the major river valleys of the Colorado River and Gunnison River, and throughout the state’s steeply incised valleys. A well-defined minimum is noted on the plains north of Denver and immediately east of the Front Range. Similarly, northwest Colorado is characterized by a deficiency in stroke activity.

5. The relationship between stroke density and elevation, with an emphasis on elevations above 3200 m (10500 ft)

To identify interactions between the full range of terrain elevations and stroke density, the state’s 3389-m
The elevation range (11 119 ft) is divided into 152-m (500 ft) sections creating 23 elevation classes from which stroke densities are calculated (Fig. 4). The elevation range classes in map form presented in Fig. 3 correspond to those presented in histogram form in Fig. 4. Because some elevation classes cross state boundaries and most cross a series of topographically and latitudinally controlled climate regimes, it is not possible to make explicit statements about relationship between stroke density and elevation for many of the elevation classes across the state of Colorado. However, some of the stronger signals in Fig. 4, such as the positive relationships found in segment B–D and the anomalous dips at label E and label F, are traceable to specific landscape controls. The remainder of this section elaborates on the topographic controls that create the shape of the histogram in Fig. 4.

A total of 98% of Colorado’s elevation below 1524 m (5000 ft) lies in the eastern portion of the state, generally covering the area east of the higher elevations that form the Cheyenne Ridge, Palmer Divide, and Raton Mesa (segment A–C in Fig. 4). Specifically, these lower elevations capture the Arkansas River valley as far west as just west of Pueblo, the northern section of the Denver metropolitan area, a strip of land west of Interstate 25 from just east of Boulder to the Fort Collins area, and the vast relatively featureless landscape that slopes into Kansas along the eastern edge of Colorado. The other 2% of the state’s elevations that lie below 1524 m (5000 ft) in the state’s western portion include the lowlands adjacent to Colorado River near the Utah border, and the extreme tip of the state’s southwestern corner. The major controls of lightning activity in the eastern lower elevations are associated with storms moving off the Front Range mountains and moving east across the plains. Lightning activity gradually increases from east to west in this region as low-level southeasterly flow interacts with topographic forcing. The small fraction (one-tenth of 1%) of the state’s elevation class below 1067 m (3500 ft) experiences slightly higher stroke densities that the adjacent elevation class because the majority of this elevation class lies in the far southeast section of the state, east of the Raton Mesa region (label A in Fig. 4).

Moving up in elevation, 78% of the state’s area between 1524 m (5000 ft) and 1829 m (6000 ft) is found on
the east side of the state, east of the Rocky Mountains.
This elevation range includes the gently sloping plains
that outline the two notable lightning maxima in
the state: the Palmer Divide region and the Raton Mesa
region. This landscape of strong topographic forcing is
indicated in segment C–D. In contrast, the same eleva-

current range on the western side of the state generally
follows lowlands near major river drainages. If the stroke
densities captured in this western portion of the elevation
range were not included in the data that forms Fig. 4, the
slope in segment C–D would be steeper (e.g., higher
stroke densities). To summarize, the lower elevations as
characterized by segment A–D are dominated by a vast,
contiguous, gently sloping landscape whose structure fa-
vors upslope flow.

With the exception of the dips at label E and label F in
Fig. 4, the information provided in segment D–F [1829 m
(6000 ft) to 3200 m (10 500 ft)] is limited in its usefulness
for gaining insight into Colorado’s lightning climatology
because, as mentioned earlier, these elevation classes
capture a host of climate types, landforms, and land-

scapes across the western and eastern slopes of the Col-
orado Rocky Mountains. Label E, however, captures the
vast (7200 km²), relatively featureless, mountain-bound
depositional surface of the San Luis Valley. With an
average annual stroke density of 1.8 km² yr⁻¹, the San
Luis Valley occupies 35% of the state’s elevation range
between 2286 m (7500 ft) to 2438 m (8000 ft).

The relative minimum at label F in Fig. 4 [3048 m
(10 000 ft) to 3200 m (10 500 ft)] corresponds to the ex-
tensive network of valleys that incise the higher terrain
regions of Colorado. Equilibrium line altitudes (ELAs)
characterize the elevation of formerly glaciated valleys.
Average late-Pleistocene glaciation ELAs in the San
Juan Mountains (Leonard 1984) and in the Front Range
(Meierding 1982) fall within this elevation class, and in
the Sawatch Range (Brugger and Goldstein 1999)
are only 175 m above the high end of the class. Examples
of these incised valleys are visible in Fig. 3 in and around
the set of three aforementioned mountain ranges.

Segment F–G reveals a rapid increase in lightning
density with elevation in the highest 11% of the state.
Most notably, stroke densities rapidly increase above
3658 m (12 000 ft), the elevations in Colorado generally
characterized by steep, glacially sculpted, frost-shattered,
near-or-above treeline rocky alpine landscapes (National
Park Service 2013). Within segment F–G, stroke densities
increase from 4.6 km² yr⁻¹ between 3048 m (10 000 ft)
and 3200 m (10 500 ft; label F in Fig. 4) to 12.4 km² yr⁻¹
at elevations above 4267 m (14 000 ft; label G in Fig. 4).
Likely topographic influences that shape this rapid increase in lightning activity with elevation are discussed in a few research papers, but the specific controls are not well understood. Cummins (2012) found that in the mountains of Colorado and northern New Mexico, the highest ground stroke densities occur in regions with the highest terrain gradient, with the highest densities typically occurring more than halfway up mountain slopes. The author offered several possible explanations for the variability in stroke density in the mountainous areas, including surface-driven turbulence, terrain roughness, along with height and slope variations of the surface electrical boundary conditions. Bourscheidt et al. (2009), in an analysis of lightning flash density over sections of the Rio Grande do Sul state of Brazil, also observed the greatest flash densities to occur where the terrain slope was greatest.

6. Conclusions

We identified relationships between stroke densities and specific landscape features, such as gently sloping surfaces and broad valleys. The increase in lightning activity by elevation in the lower elevations corresponds to the broad and gently sloping surfaces in the eastern sections of the state that ascend the Palmer Divide and Raton Mesa, regions of strong topographic forcing and available low-level atmospheric moisture. With the exception of the vast flat-floored and mountain-bound San Luis Valley, the complex topography captured in the intermediate elevation classes blurs the identification of specific landscape controls on lightning activity. The relative stroke density minimum found between 3048 m (10 000 ft) and 3200 m (10 500 ft) corresponds to the extensive network of steep-walled glacial valleys that dissect the higher elevations of the major mountain ranges across the state. Our analysis corroborates extant research that suggests a steep terrain gradient and an increase in surface-generated turbulence enhance lightning activity in elevations above about 3200 m (10 500 ft). Plotting elevation against stroke density year by year from 1996 to 2012 demonstrates that the 2002–03 NLDN upgrades improved stroke detection efficiency in the higher elevations (Fig. 1). In Colorado, these enhancements are integral for detecting the lighting–landscape relationships above about 3200 m (10 500 ft).

This paper demonstrated that the visual and analytical products of GIS, such as maps, histograms, and statistical measures, can help create highly detailed lightning climatologies for user-defined regions. The next steps for developing a complete lightning climatology of Colorado are to explore discrete regions within the state across elevation ranges and incorporate a temporal component into the analyses. We will focus our future research on select regions of Colorado, including the Denver Cyclone vorticity zone (DCVZ; Szoke et al. 1984) and the San Juan Mountains. Specifically, the authors will explore the role of the DCVZ in enhancing and limiting lightning activity, and the influence of the southwestern monsoon on the lightning climatology of the San Juan Mountains.

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REFERENCES


